

# A SPACE BASED INTERNET PROTOCOL SYSTEM FOR LAUNCH VEHICLE TRACKING AND CONTROL

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## BIOGRAPHIES

Mr. Bull is an Electrical Engineer in the Guidance, Navigation and Control (GN&C) Center of NASA's Goddard Space Flight Center. Mr. Bull's primary responsibilities are in development of GPS systems for sub-orbital payloads on balloons, sounding rockets and remote sensing aircraft platforms. He received a BS degree in Aerospace and Ocean Engineering from Virginia Polytechnic Institute and State University in 1980. He joined NASA in 1990 as a Systems Engineer for the TOPEX Radar Altimeter.

Mr. Morgan is an Electrical Engineer in the Real Time Software Engineering Branch (RTSEB) of NASA's Goddard Space Flight Center. He is the project manager for the "Flight Modem" project. Mr. Morgan has served as project manager, product design lead, and telemetry engineer for several NASA projects over the past 10 years. He has also provided resource planning, cost, and analysis support for down range missions such as X-33, X-34 and JASON. He received a BSEE degree from Old Dominion University in 1991. Mr. Morgan joined NASA in 1990 as a co-op student and has served as an electronics engineer since 1992.

Mr. Streich has 34 years experience in telemetry acquisition systems for orbital and range tracking including Project Apollo TLI and re-entry operations, 15 years at Vandenberg AFB, 3 years at Astro Link to design and test telemetry receivers, 6 years at Edwards AFB to modernize the range with nine new autotrackers including four mobile trackers with support equipment including automated setup and test, and 7 years at Wallops integrating the EOS Polar Ground Network stations in Alaska, Norway, McMurdo and Wallops.

Mr. Grant has 10 years experience in telemetry systems for orbital, suborbital, and range tracking including NASA Sounding Rocket engineering testing stations and operations receiving stations, and 6 years at Wallops integrating the EOS Polar Ground Network stations in Alaska, Norway, McMurdo and Wallops as well as designing and installing mobile telemetry tracking systems.

## ABSTRACT

Personnel from the Goddard Space Flight Center Wallops Flight Facility (GSFC/WFF) in Virginia are responsible for the overall management of the NASA Sounding Rocket and Scientific Balloon Programs. Payloads are generally in support of NASA's Space Science Enterprise's missions and return a variety of scientific data as well as providing a reasonably economical means of conducting engineering tests for instruments and devices used on satellites and other spacecraft. Sounding rockets used by NASA can carry payloads of various weights to altitudes from 50 km to more than 1,300 km. Scientific balloons can carry a payload weighing as much as 3,630 Kg to an altitude of 42 km. Launch activities for both are conducted not only from established ranges, but also from remote locations worldwide requiring mobile tracking and command equipment to be transported and set up at considerable expense. The advent of low earth orbit (LEO) commercial communications satellites provides an opportunity to dramatically reduce tracking and control costs of these launch vehicles and Unpiloted Aerial Vehicles (UAVs) by reducing or eliminating this ground infrastructure. Additionally, since data transmission is by packetized Internet Protocol (IP), data can be received and commands initiated from practically any location.

A low cost Commercial Off The Shelf (COTS) system is currently under development for sounding rockets that also has application to UAVs and scientific balloons. Due to relatively low data rate (9600 baud) currently available, the system will first be used to provide GPS data for tracking and vehicle recovery. Range safety requirements for launch vehicles usually stipulate at least two independent tracking sources. Most sounding rockets flown by NASA now carry GPS receivers that output position data via the payload telemetry system to the ground station. The Flight Modem can be configured as a completely separate link thereby eliminating the requirement for tracking radar.

The system architecture that integrates antennas, GPS receiver, commercial satellite packet data modem, and a single board computer with custom software is described along with the technical challenges and the plan for their resolution. These include antenna development, high Doppler rates, reliability, environmental ruggedness, hand over between satellites, and data security. An aggressive test plan is included which, in addition to environmental testing, measures bit error rate, latency and antenna patterns. Actual launches on a sounding rocket and various aircraft flights have taken place. Flight tests are planned for the near future on aircraft, long duration balloons and sounding rockets. These results, as well as the current status of the project, are reported.

## INTRODUCTION

Four types of airborne vehicles used by NASA at Wallops Island and other ranges require telemetry, tracking and control (TT&C) support – Launch Vehicles, Scientific Balloons, Unpiloted Aerial Vehicles (UAVs) and Aircraft. The requirements vary greatly according to the platform type, mission and geographical location. Aircraft may be tracked for performance evaluation or for precise location necessary to evaluate remote sensing data. UAVs are tracked for vehicle navigation and control, control of experiments, and for range safety purposes. Scientific Balloons, including the Ultra Long Duration Balloon under development at WFF must be tracked for safety, data collection and for control of its experiments and systems. Of primary interest in this paper are Sounding Rockets. WFF conducts launch campaigns not only from Wallops Island and other established foreign and domestic ranges, but also from mobile ranges worldwide. Telemetry, tracking and control are a large portion of the cost involved in these operations. Position, Velocity and Time data provided by GPS is used for experiment evaluation, guidance and navigation, vehicle performance analysis, payload recovery, measurement of separation and relative velocity of multiple payloads and as a source of slaving for telemetry, radar and optical tracking devices. The Range Commanders Council Global Positioning System (GPS) Range Safety Applications

Subcommittee has declared GPS to be an excellent data source for flight safety decision-making. Indeed it is already being used in some cases as the primary range safety data source.

Historically, the primary method of tracking and control of many of these vehicles has been radar and ground based RF telemetry. As with most ranges, WFF is finding the high cost of radar operation and maintenance a difficult burden to justify in light of savings available from using GPS. This is particularly true at temporary, mobile ranges

GPS has been used on WFF sounding rockets for seven years and is now considered standard equipment on most launches. The conventional method is to multiplex the pseudorange data with the payload telemetry and downlink it to a ground based tracking antenna, strip out the GPS data and perform a real time inverse differential solution which is distributed to range control users. Although this may be used to replace or augment radar, it still requires complex tracking and uplink equipment that must be operated by on-site personnel. It is restricted to line of sight operation.

The new approach eliminates many of these restrictions. The flight modem transmits the tracking data to a commercial low earth orbiting communications satellite that relays it to a ground station (gateway). Communication is full duplex and commands can be sent to the payload. An Internet Protocol (IP) connection at the gateway allows worldwide communications with the payload from any (or several) sources. The potential savings in terms of operations and infrastructure is enormous. In addition to metric tracking data from the GPS, INS and housekeeping data may be included.

## GPS SYSTEM

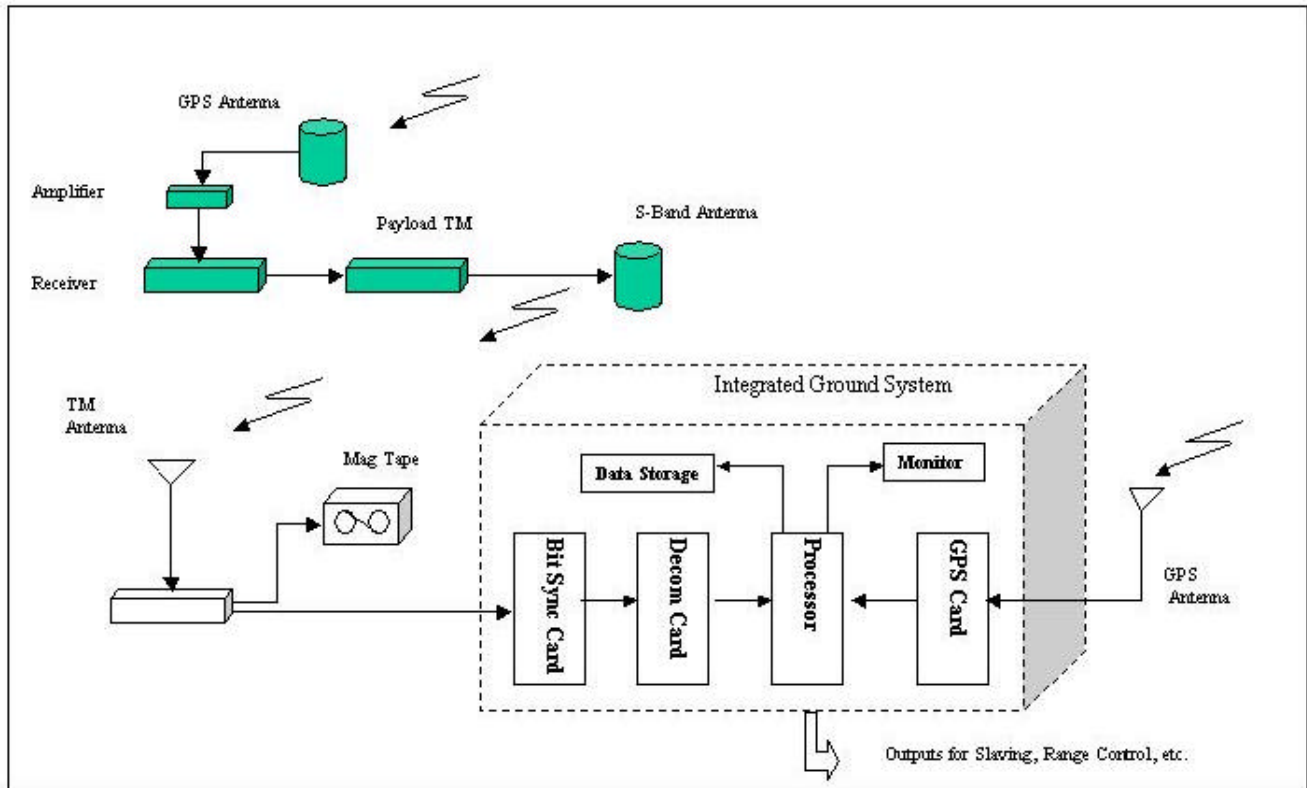
The GPS system flown on NASA sounding rockets is made up of flight and ground hardware and processing software. (Fig 1)

The flight hardware consists of three pieces – an antenna, a preamplifier and a GPS receiver along with necessary wiring.

The antenna, designed and manufactured by New Mexico State University Physical Science Laboratory, (NMSU/PSL) consists of eight right hand circularly polarized radiating elements fabricated on two 1/8" thick by 5.5" width half rings which are joined together and flush mounted in a groove milled into the skin of the rocket's payload section. The two sub-arrays are fed in-phase with a coaxial power divider harness. A radome is

incorporated into each subarray to protect against heat. The pattern is fairly circular with -8dBic at 90% full coverage. Due to the elements being fed in-phase, a null of 3 to 5 dB at the 3dB down level exists along the axis of

the rocket. The VSWR is approximately 2 with a bandwidth of about 10 MHz.



**Fig 1. GPS with Conventional Telemetry**

The COTS Trimble preamplifier provides 42dB of gain. Power for the preamplifier is provided via the coaxial cable. The frequency range is 1565 to 1585 MHz with 15 dB rejection at 1610 MHz and 60 dB rejection at 2200 MHz.

The receiver consists of two printed circuit boards integrated into a 3" x 5" x 1" aluminum box. One board is the Ashtech G12 HDMA GPS engine manufactured by the Magellan Corporation and the other, designed and built at WFF, provides power conditioning, communications format conversion, and analog to digital conversion. A plastic potting compound stabilizes the boards against vibrations.

The G12 HDMA is a 12 channel L1 C/A code receiver which features wide tracking loops to accommodate the high Doppler rate involved in missile launches, low data latency, rapid acquisition of lock and is capable of

outputting at up to a 10 Hz update rate. A highly stable and accurate 1 PPS signal is available for time tagging and synchronization of other payload data. Data is output as a serial RS-422 stream. Parameters such as signal level and elevation masks, tracking loop bandwidths and satellite exclusion are selectable and a variety of data formats are available. In addition to position, velocity and time, pseudorange data and carrier phase information is included and may be used on the ground to calculate a highly accurate differential solution. An onboard memory saves almanac data and operating parameters in order to avoid programming in the field.

A waiver is granted to NASA as a U.S. Government agency to allow operation of the receiver above the 1000 knots (velocity) and 60,000 ft (altitude) limit imposed by the International Trade in Arms Reduction (ITAR) act restrictions.

The differential ground station is housed in a portable "lunchbox" size computer with a self-contained keyboard and popup monitor that can accommodate bit synchronizer, decommutator and GPS computer boards. The full set of multiplexed data from the entire payload is input to a bit synchronizer card where a matched-filter integrates the signal and clocks it out as a reconstructed PCM bit stream along with timing clocks. The reconstructed data stream and clocks are sent to a decommutator card, which strips the GPS data from the stream by comparison with a replica of the expected frame sync pattern in a digital correlator. The decommutator can be programmed for various bit rates and frame synch patterns. A Novatel GPSCard receiver resides in the computer and is connected to a nearby antenna, whose position has been accurately determined by a survey. This provides data for real time differential corrections.

Real time differential tracking with the system is accurate to less than 10 m real time with post mission processing better than 1 m. Velocity accuracy is better than 1 m/s real time and up to 10 cm/s post processed. Precision of actual post processed flight data has been shown to be 4 cm [5]. Further information on the GPS system is available from reference [1].

## GLOBALSTAR

Use of satellites to relay TT&C data is not a new concept. Inmarsat and Argos have been used on NASA's scientific balloons and for locating rocket payloads for recovery. NASA's Tracking and Data Relay Satellite System (TDRSS) designed for relay of data from scientific satellites has such a capability although equipment costs and scheduling make it unattractive for our purposes. Several of the operational or proposed LEO constellations such as Iridium and ICO Globecom are candidates and are being explored for future use. The constellation selected is Globalstar. Globalstar offers global commercial IP space based communications with COTS Original Equipment Manufacturer (OEM) products to support full duplex, low bandwidth data requirements on a satellite constellation. Operating at an altitude of 1,440 km (876 miles) the 48 satellites of the Globalstar constellation are placed in eight orbital planes of six satellites each, inclined at 52 degrees.

. They provide service from 70 degrees North latitude to 70 degrees South latitude. The satellites have "bent-pipe" architecture and on a call up basis transmit CDMA data through a gateway where the call is then routed locally through the terrestrial telecommunications system. The user terminal must be a dedicated server with a direct connection to the internet thereby avoiding any delay in reception.

## THE FLIGHT MODEM

The Flight Modem is comprised of three parts: A combined transmit and receive antenna, a computer and a modem.

The Flight Modem antenna is very similar in construction to the GPS antenna and is also a product of NMSU/PSL. It is a 14 inch diameter, 2-piece wrap around antenna with center carrier frequencies of 1618.5MHz (1610-1625 MHz Bandwidth) and 2292.5MHz from (2283-2499 MHz Bandwidth) using LHCP for both frequencies. It is built into two half-cylinder subarrays with a feed harness and power divider/combiners and fitted into a recess milled into the payload skin.

The flight modem computer is a RLC Enterprises Inc CE Minus/CE Plus embedded computer system running Windows CE 3.0 operating system. The CE-Plus is an input/output (I/O) interface expansion board. The CE-Minus, a single-board computer, provides the central processing unit (CPU), memory, clock, graphics and PCMCIA controllers.

The flight computer serves three primary functions: controlling the modem, formatting data for the modem and recording data onboard.

The computer initiates calls to the Globalstar satellite and is programmed to redial in event of a lost connection. A gateway may be pre-selected in order to minimize dial up time.

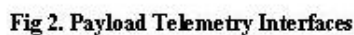
The flight computer takes in RS-422 serial data from the GPS and logs the data along with system status information from the satellite to onboard memory. The data includes received signal strength indication, location as computed by the satellite system from travel time to several of the satellites in the constellation and error information. Storage requirements are minimized by recognizing the line feed carriage return character at the end of each line of data. The GPS data is sent to the modem as RS-232.

The Qualcomm GSP-1620 modem, a COTS product is configured to appear as a standard Hayes 33.6 data modem. Communications between the flight computer and GSP-1620 are at 38.8 kbaud. It permits full duplex operation between the user and the Internet at 9600 baud for sustained data rates of 8200 bps including required retransmissions for error correction.

The bit rate is 9600 bps modulating a 614,400 chip per second rate to produce Code Division Multiple Access (CDMA) or spread spectrum. The symbol rate is Quadrature Phase Shift key (QPSK) modulated on one carrier in the 1610-1625 MHz band.

also decides which satellites to use and handles handovers.

Uplink data may be sent from any Internet connection via the gateway and satellite and is received at 2483 to 2500 MHz.



All components were encased in a plastic potting compound and subjected to vibration testing prior to launch. Further information on the Flight Modem is available from reference [2].

## TEST FLIGHT

On February 19, 2001, the Flight Modem was tested on a payload module from the Wallops Flight Facility (WFF) of NASA's Goddard Space Flight Center which was launched on an Improved Orion sounding rocket from Esrange, near Kiruna, Sweden. In addition to the Flight Modem, the payload consisted of two GPS receivers, a WFF Ashtech G12 based receiver for use by Esrange in evaluating and preparing the range for inclusion of GPS technology and a BAE Allstar receiver for possible use on ballistic missile payloads mission.

The launch was a practice flight for the larger Maxus-4 rocket to be used by ESA for microgravity experiments. At 81 km, the maximum altitude was lower than many sounding rockets, but the dynamics were typical of other missions. Maximum acceleration was 17 g's and the total velocity peaked in excess of 1100 m/s. The payload spun at about 4 rps until it is despun after separation from the booster.

The interfaces with the flight modem and the conventional telemetry system is shown in Fig 2. A RF power splitter is used to divert a portion of the received GPS signal to a GPS receiver that was part of a separate experiment. An output of the WFF/Ashtech receiver is also sent to the conventional telemetry system and, in addition to being used by Esrange for tracking, antenna slaving and Instantaneous Impact Prediction, provided a source for comparison with the GPS data recorded on the Flight Modem hard drive.

Unfortunately, the Finland gateway, which services the Kiruna region, was configured only for voice and was not yet ready to connect with terrestrial Public Switched Telephone Networks (PSTN) to make use of the full duplex IP capabilities. In spite of this limitation, it was determined that a meaningful test of the flight system could be undertaken in conjunction with terrestrial based demonstrations performed in the United States using data configured gateways. During the rocket flight, Markov calls were used to evaluate the data. Markov calls are loopback calls, originated by the Flight Modem that simulate the data flow and provide signal quality information from the Globalstar satellite. The data returned and recorded on the hard drive of the Flight Modem computer, confirms the call, notes its duration, identifies the gateway used, and logs the signal strength received by the satellite along with any bit or frame

errors. GPS data was stored in a separate file for post flight evaluation. Additionally, Call Activity Records (CAR) and Call Detail Records (CDR) were requested and received from the Finland Globalstar ground station which indicated usage of the GSP-1620 modem for billing purposes. Activity and detail records indicate call start and stop times, latitude and longitude of the call location, and identity of the particular satellite used to make the call. Time data from these records was used to align the Markov data with the GPS and flight events.

During integration and testing, some radio frequency interference was noted. During transmissions by the flight modem, the GPS receiver was losing lock on satellites. This was not altogether surprising, given that the antennas were separated by only 7 inches. The LNA used with the receiver only attenuates 15 dB at 1610 MHz. A band pass filter was retrofitted to provide additional 55 dB attenuation. No further RFI was noted in further testing. Interestingly, a BAE Allstar receiver sharing the same GPS antenna (but not the LNA) was immune to the interference as was a Mitel Orion based unit with a separate antenna.

The first call was placed several minutes before launch. Unfortunately, the call was terminated for unknown reasons 19 seconds before lift off. The Flight Computer commanded a redial, but communications were not re-established until 1 minute and 4 seconds into the flight. This prevented an important objective, the demonstration of the ability to maintain communications during the period of highest acceleration and resulting Doppler rate during the flight, from being realized. However, the second call was automatically initiated while the payload was traveling at 750 m/s and with a spin rate of 4 Hz. It was maintained through the despin sequence, nosecone ejection, motor separation, and for several minutes after the parachute had been deployed. Contact was again lost and regained with the payload on the ground. Reasons for termination of the calls have not been determined, but at 68 degrees, the latitude at which we operated was near the limit of coverage of the 52-degree inclination Globalstar constellation. The sequence of events is shown on Fig 3. Also shown is the signal to noise ratio calculated from the RSSI reported by the Globalstar satellite and corrected for coding gain and the Frame Error Rate. Except for the two periods during which the calls are interrupted, the frame errors are seen to be less than 1%. In reality, the power is adjusted down until the frame error reaches the 1% mark. These frames are retransmitted and the data is error free. [4]

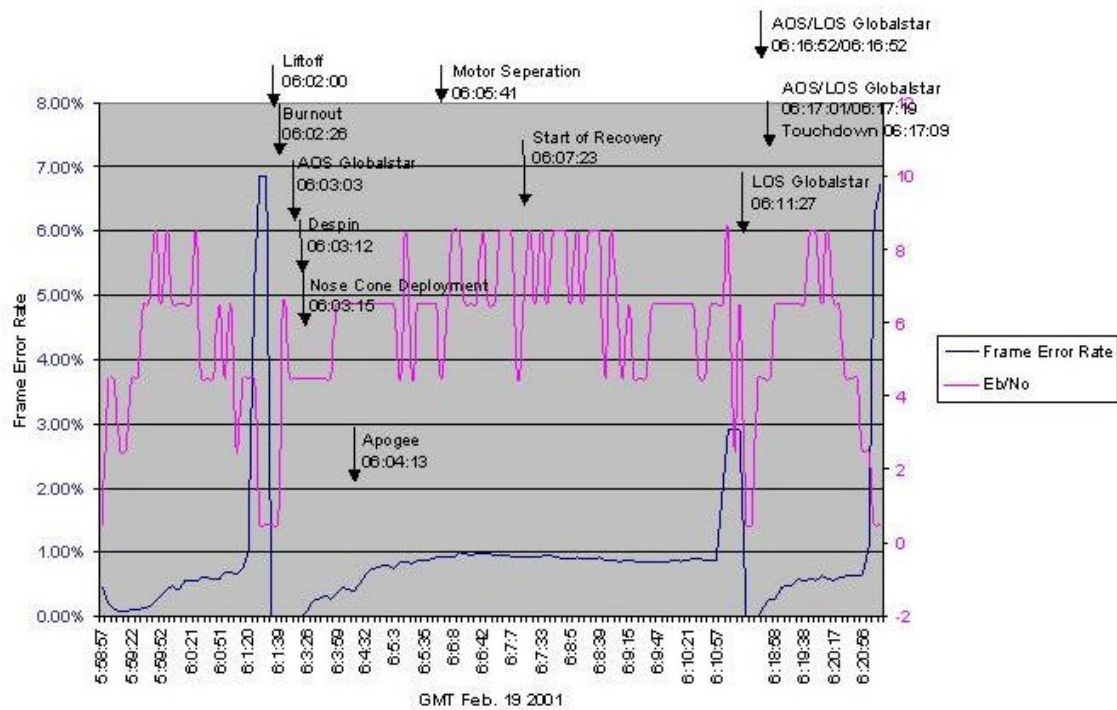


Fig 3 Flight Sequence

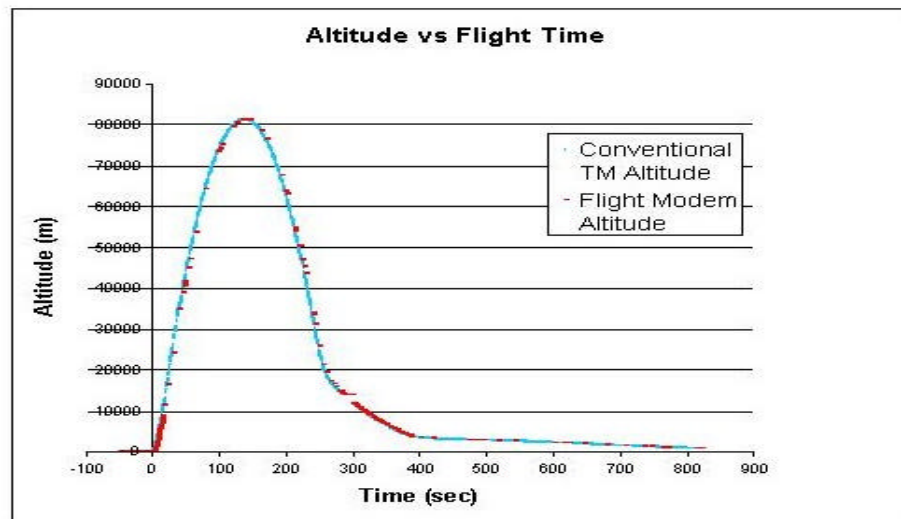


Fig 4. Attitude vs Flight Time

Fig 4. is a plot of the altitude vs. time for both the data received by the conventional telemetry and that stored on the flight modem hard drive. All points recorded were the same as transmitted by the conventional system. However, due to a programming error fewer data points were recorded on the hard drive.

## CONCLUSIONS

The use of a flight modem for space based telemetry, tracking and control of various NASA platforms shows great promise for effecting cost reduction. A prototype system has been built and tested on aircraft and a sounding rocket. The first flight test on a sounding rocket showed the ability to transmit tracking data during flight. Two difficulties prevented the test from fully demonstrating the capabilities of the concept. Limited coverage of the selected communications satellite system at the high latitude of the launch site caused occasional drop outs. Occurrence of one of these just prior to launch caused lost of transmission during the highest acceleration period of the flight. These drop outs were never experienced in later low latitude test flight of greater than one hour duration on aircraft. The other limitation, unavailability of a data enabled gateway at the launch site prevented use of the Internet Protocol abilities of the system, but has been demonstrated in other regions.

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